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A SIMPLE MODEL FOR THE SIZE-EVOLUTION OF ELLIPTICAL GALAXIES

Sadegh Khochfar & Joseph Silk
Department of Physics, Denys Wilkinson Bldg., University of Oxford, Keble Road, Oxford, OX1 3RH, UK

ABSTRACT

We use semi-analytical modelling of galaxy formation to predict the redshift-size-evolution of elliptical galaxies. Using a simple model in which relative sizes of elliptical galaxies of a given mass correlate with the fraction of stars formed in a star burst during a major merger event, we are able to reproduce the observed redshift-size-evolution. The size evolution is a result of the amount of cold gas available during the major merger. Mergers at high redshifts are gas-rich and produce ellipticals with smaller sizes. In particular we find a power-law relation between the sizes at different redshifts, with the power-law index giving a measure of the relative amount of dissipation during the mergers that lead to the formation of an elliptical. The size evolution is found to be stronger for more massive galaxies as they involve more gas at high redshifts when they form, compared to less massive ellipticals. Local ellipticals more massive than 5×10^{11} M$_\odot$ will be approximately 4 times larger than their counterparts at $z = 2$. Our results indicate that the scatter in the size of similar massive present day elliptical galaxies is a result of their formation epoch, with smaller ellipticals being formed earlier.

Subject headings: galaxies: elliptical – galaxies: interaction– galaxies: structure – galaxies: evolution – methods: numerical

1. INTRODUCTION

Elliptical galaxies have been shown to have formed the bulk of their stars at high redshifts within an intensive star burst (e.g. Cimatti et al. 2004; Thomas et al. 2005), supporting a scenario in which elliptical galaxies formed in a 'monolithic' collapse and then continued evolving passively. On the other hand, many stellar dynamical properties of elliptical galaxies can be explained by the merger of similar massive galaxies (e.g. Barnes & Hernquist 1992; Naab & Burkert 2003; Naab, Jesseit & Burkert 2006) as initially proposed by Toomre & Toomre (1972). The predicted merger rate of galaxies within the CDM paradigm and the observations are in fair agreement (Khochfar & Burkert 2001). As to the mainly old stellar populations of elliptical galaxies, De Lucia et al. (2006) show that these can be recovered within the merger scenario which comes as a consequence of massive elliptical galaxies forming by dry mergers between elliptical galaxies (Khochfar & Burkert 2003). In addition, it has been shown that dry mergers can indeed explain the kinematical properties of massive elliptical galaxies (Khochfar & Burkert 2005; Naab, Khochfar & Burkert 2006). and might be able to even account for the partially depleted cores of luminous ellipticals (e.g. Graham 2004).

The size evolution of elliptical galaxies could serve as an additional possible test for these two models. Recent size measurements of ellipticals carried out at high redshift indicate that they are much smaller than their local counter parts (Daddi et al. 2005; Trujillo et al. 2005). Numerical simulations by Naab & Trujillo (2005) which use self-consistent cosmological orbital parameters (Khochfar & Burkert 2006) to set up mergers between disk galaxies, find that the size of the remnant is of the same order as the size of the progenitor disk. The simulations of Naab & Trujillo (2005) did not include any gas or star formation in contrast to simulations carried out by Springel & Hernquist (2005). The latter authors find that those stars which existed in the progenitor disks before the merger, which we call the *quiescent* component, have a ~ 5.7 times larger effective radius than the stars which formed during the merger in a violent star burst, which we will call the *merger* component of the elliptical. However, the ratio of the effective radii of the two components is very likely to depend on the structure of the progenitors and on the way the merger takes place. The total effective radius of the remnant will depend on the mass fraction of each component, with a larger merger component leading to a smaller remnant.

Recently, Khochfar & Silk (2005, hereafter KS) investigated the fraction of merger and quiescent components in early-type galaxies, finding that the quiescent component is decreasing with redshift and increasing with mass up to a characteristic mass scale $M_C = 3 \times 10^{10} M_\odot$ (Kauffmann et al. 2003, hereafter K03) at which it becomes constant. In this letter we follow up on their study and predict the size-evolution of elliptical galaxies within the CDM-paradigm.

2. MODEL

We use semi-analytical modelling of galaxy formation to predict the merger and quiescent components of elliptical galaxies. The dark matter history is calculated using the merger tree proposed by Somerville & Kolatt (1999) with a mass resolution of $2{\times}10^9 M_\odot$. The baryonic physics within these dark matter halos is calculated following recipes presented in Springel et al. (2001) including a model for the reionizing background by Somerville (2002). In our simulation, we assume that elliptical galaxies form whenever a major merger ($M_1/M_2 \leq 3.5$ with $M_1 \geq M_2$) takes place. We assume that during this process all the cold gas which was in the progenitor disks will be consumed in a central starburst, adding to the spheroid mass, and that all stars in the progenitor disks will be scattered into the spheroid too. Furthermore we allow the stars of satellite galaxies in minor mergers to also contribute to the spheroid. During the evolution of

Electronic address: sadeghk@astro.ox.ac.uk; silk@astro.ox.ac.uk

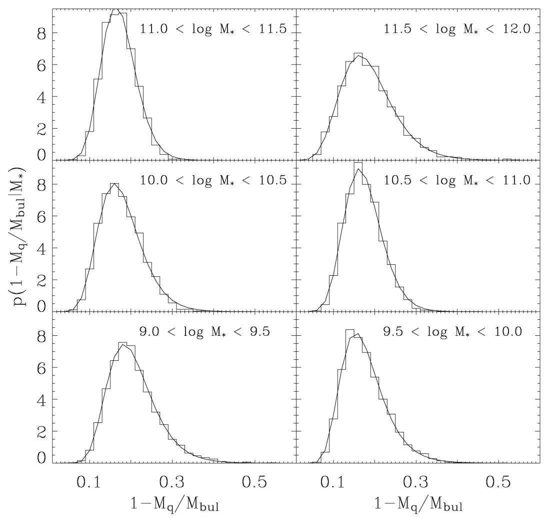

FIG. 1.— Histograms show the conditional probability density $p(1 - M_q/M_{bul}|M_*)$ of the merger component in spheroids as a function of stellar mass M_* in six different mass bins. Solid lines show log-normal distributions fitted to the data. Results are shown for elliptical galaxies only.

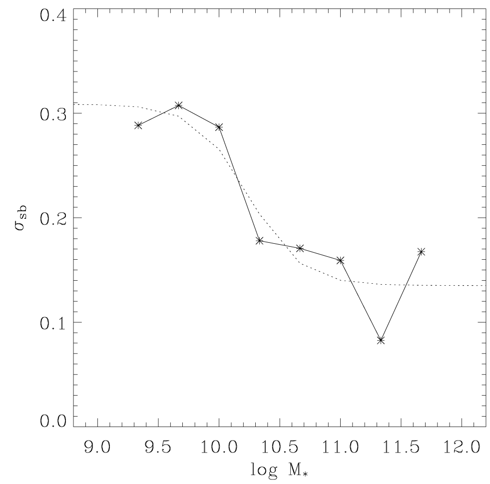

FIG. 2.— Dependence of the variance $\sigma_{\rm sb}$ of the conditional probability density $p(1 - M_q/M_{bul}|M_*)$ as a function of stellar mass M_* of elliptical galaxies. The dotted line shows the fit using the empirical formula of S03.

a galaxy, we keep track of the origins of all stars brought into the spheroid and attribute them to two categories, merger and quiescent, where the first incorporates stars formed during a starburst in a major merger and the latter includes stars previously formed in a disk and added to the spheroid during a major merger. Each star will carry along its label and not change it, which means that if a star was made in a merger of two progenitor galaxies and the remnant of that merger participated in another merger, the star will still contribute to the merger component of the final remnant.

For more modelling details, we refer the reader to KS and references therein. Throughout this paper, we use the following set of cosmological parameters: $\Omega_0 = 0.3$, $\Omega_\Lambda = 0.7$, $\Omega_b/\Omega_0 = 0.15$, $\sigma_8 = 0.9$ and $h = 0.65$. We note here that running our code with the latest cosmological parameters from the WMAP mission (Spergel et al. 2006) only changes our results slightly and that most of the effects are compensated for by the free model parameters for the star formation efficiency and the supernova feedback.

3. RELATIVE SIZES OF ELLIPTICALS

As we have mentioned above, the relative effective radii of merger and quiescent components are very likely to be dependent on the physical properties under which the merger takes place. To minimise this effect, we compare the relative sizes for ellipticals of similar mass. By doing so, we can assume that e.g. the potential depth is the same and that feedback effects have the same efficiency. Furthermore, it has been shown that the orbital parameters of merging halos are on average independent of the remnant halo mass and redshift (Khochfar & Burkert 2006), which allows us to assume that merging will take place on average with the same orbital set-up.

The SDSS study revealed that the size distribution of galaxies with the same mass is log-normal and that the variance $\sigma_{\ln R_{\rm e}}$ of the distribution is a function of mass (K03; Shen et al. 2003, hereafter S03). Above $\sim 10^{10}$ $\mathrm{M}_\odot$, the variance drops until it becomes approximately constant for galaxies more massive than $\sim 10^{11}$ $\mathrm{M}_\odot$. S03 show that their model, in which elliptical galaxies form by continued merging of galaxies, could reproduce the scatter in the size distribution of massive elliptical galaxies, by assuming the size distribution of the progenitors to be log-normal. However, the origin of the scatter in the size distribution of the progenitors remains not well understood. We start off by investigating the scatter in the merger component and comparing it to the scatter in the observed size distribution of early-type galaxies.

In Fig. 1, we show the distribution of the merger components found in elliptical galaxies of various masses M_*, where elliptical galaxies are those having more than 65% of their stellar mass in their bulge component. We have fitted the data with log-normal distributions following K03 and S03 as:

$$p\,(x|M_*) = \frac{1}{\sqrt{2\pi}(x-a)\sigma_{\rm sb}} \exp\left(-\frac{\ln^2[(x-a)/b]}{2\sigma_{\rm sb}^2}\right) \tag{1}$$

with a, b and $\sigma_{\rm sb}$ as free parameters, $x \equiv 1 - M_q/M_{bul}$ as the merger component in a spheroid of mass M_{bul}, and M_q as the quiescent component of that spheroid. As can be seen, the log-normal distribution provides excellent fits to our simulated data. We can now try to compare our variance $\sigma_{\rm sb}$ as a function of galaxy mass to the observed variance $\sigma_{\ln R_{\rm e}}$ in the SDSS. S03 give an empirical fitting formulae to their results,

$$\sigma_{\rm sb} = \sigma_2 + \frac{\sigma_1 - \sigma_2}{1 + (M_*/M_0)^2} \tag{2}$$

with σ_1, σ_2 and M_0 as free parameters. The fit of Eq. 2 to our data is shown in Fig. 2. Our data seems to be fitted well by Eq. 2 and the trend in the observations can be recovered. The mass scale M_0, characteristic for the transition point from large scatter to small scatter in the distributions is best fitted by a value of $M_0 \approx 1.7 \times 10^{10}$ $\mathrm{M}_\odot$ in our simulations, which is a about a factor 2 smaller than the value of 3.89×10^{10} $\mathrm{M}_\odot$ suggested by S03 but still in reasonable agreement. For completeness we also give the values of the other fitting parameters which are $\sigma_1 = 0.31$ and $\sigma_2 = 0.14$.

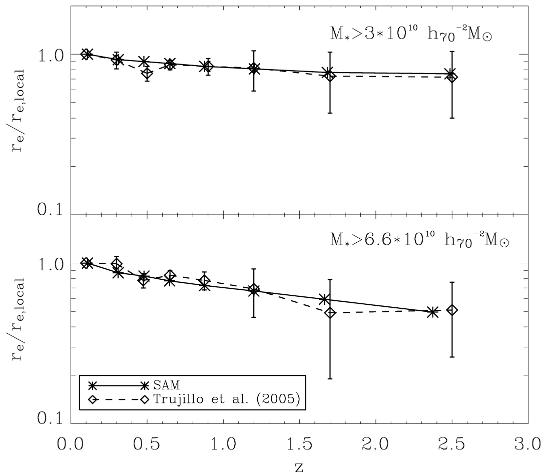

FIG. 3.— The evolution of sizes for early-type galaxies with respect to the sizes of their local counter parts at a redshift $z = 0.1$. The upper panel shows the size-evolution for early-type galaxies larger than $3 \times 10^{10} h_{70}^{-2}$ M$_\odot$ and the lower panel for early-type galaxies larger than $6.6 \times 10^{10} h_{70}^{-2}$ M$_\odot$.

The results presented here suggest that the scatter in merger components $1 - M_q/M_{bul}$ behaves like the scatter in the size distribution of elliptical galaxies. We now make the simplified assumption that for each mass bin

$$\ln(1 - M_q/M_{bul}) \propto \ln(R_{\rm e}), \tag{3}$$

where $R_{\rm e}$ is in units of kpc and the proportionality constant reflects the average physical conditions that led to the formation of the elliptical galaxy and. We note that other effects may influence the relative sizes of elliptical galaxies too and that we here only focus on the contribution to it by the merger component. Using the assumption of proportionality one can now calculate the relative sizes of elliptical galaxies of the same mass by knowing their different merger components and using:

$$R_{\rm e}(z_1) = R_{\rm e}^{1/d}(z_0) \quad \text{with } z_1 > z_0, \tag{4}$$

with $d \equiv \ln(1 - M_{q,0}/M_{bul})/\ln(1 - M_{q,1}/M_{bul})$ as the dissipation factor which gives a measure of the relative amount of dissipation that led to the formation of an elliptical. The scatter in the size distribution of ellipticals decreases with mass and later becomes constant. The reason for the same behaviour in the scatter of the merger component is that most massive ellipticals have their last major merger in a small redshift window not too far back in time. As a consequence the conditions regarding the gas fraction involved in the merger are very similar and the scatter is small.

4. SIZE EVOLUTION OF ELLIPTICALS

We now can test size evolution as a function of redshift predicted by Eq. 4 for elliptical galaxies of a given mass and compare it to the observations. Since we can only predict relative sizes between elliptical galaxies of approximately the same mass, we will normalise sizes to the SDSS sample. We calculate the size evolution for the same redshifts presented in Trujillo et al. (2005). The authors took the mean effective radii of the $\ln(R_{\rm e})$ distribution for galaxies above two mass thresholds of $3 \times 10^{10} h_{70}^{-2}$ M$_\odot$ and $6.6 \times 10^{10} h_{70}^{-2}$ M$_\odot$ from the SDDS sample of early-type galaxies and divided the effective radii of early-type galaxies at higher redshifts by this value. After arranging their galaxies in various redshift bins they calculated the means of these ratios and presented these values. We here use the same method to compare our results to theirs. Our zero-point for individual galaxies is taken to be the mean value of $1 - M_q/M_{bul}$ in our $\ln(1 - M_q/M_{bul})$ distribution for galaxies of the same mass at a redshift of $z = 0.1$. In Fig. 3 we show the expected evolution of sizes. For both cases of limiting masses, the agreement is excellent. It appears that the difference in sizes is more significant for massive early type galaxies. In Fig. 4 we predict the size-evolution in four different mass ranges based on the relative amount of their merger component. While local early-type galaxies between 10^{10} M$_\odot$ and 10^{11} M$_\odot$ are around 1.25 times larger than their counterparts at $z = 2$, local early types with masses larger than 5×10^{11} M$_\odot$ will be approximately 4 times larger than their counterparts at $z = 2$. This dramatic change in sizes in our model results from massive galaxies at high redshifts forming in gas-rich mergers while galaxies of the same mass at low redshifts form from gas-poor mergers (KS). This size-evolution might be an overestimate as the modelled galaxies suffer from over cooling of gas (KS) which is likely to overestimates the merger component at high redshift and the quiescent component at low redshift due to the shorter time between consecutive major mergers at high redshifts compared to low redshifts.

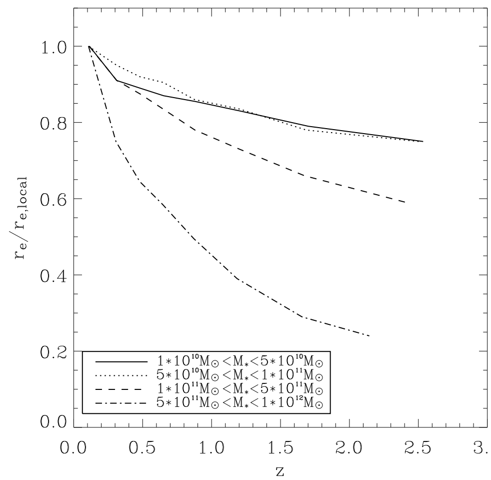

FIG. 4.— The predicted evolution of sizes for early-type galaxies with respect to the sizes of their local counter parts at a redshift $z = 0.1$ divided into four different mass bins.

5. DISCUSSION AND CONCLUSIONS

We have connected the scatter in the merger components $1 - M_q/M_{bul}$ with the scatter in the sizes of elliptical galaxies. Following KS, the scatter in the merger components of elliptical galaxies is a result of different formation epochs. Ellipticals forming early have larger merger components, as they were formed in gas-rich mergers, hence ellipticals with smaller effective radii must have formed earlier. We tested this assumption by predicting the size-evolution of elliptical galaxies at different redshifts and the agreement with the data of Trujillo et al. (2005) is excellent. It is important to note that we normalise the proportionality in our relation between the merger component and the effective radius by the observed scatter in the local galaxy sample, and then go ahead and predict how sizes at earlier redshifts compare to local sizes.

Our results demonstrate that the strongest size evolution is for massive elliptical galaxies. Local early-types with masses larger than 5×10^{11} $M_\odot$ will be approximately 4 times larger than their counterparts at $z = 2$. This extreme size-evolution is a reflection of the progenitors having larger gas fractions at high redshifts and becoming more 'dry' at low redshifts. In addition the low redshift progenitors have stellar disks that are more massive than the available amount of cold gas, hence increasing the quiescent fraction of the remnant. The progenitors however, are bulge dominated with a disk component not more massive than $\sim 20\%$ of the total mass, thus the size-evolution appears to be connected to the occurrence of bulge-dominated dry mergers with time. The most massive elliptical galaxies in our simulations undergo on average between one and two substantial dry mergers between $z = 2$ and today.

We find that the relative amount of dissipation involved in the mergers relates to the size by a power-law as described in Eq. 4 where the power-law exponent d is the dissipation factor. If this relation holds one can try to measure the relative amount of dissipation by measuring the relative sizes of recently formed ellipticals of the same mass at different redshifts. Even though theoretically it sounds straightforward to measure the dissipation factor we acknowledge that it is observationally not an easy task. The main problem here will be to identify elliptical galaxies that just formed. This is important as e.g. continued accretion of satellites or cold gas and subsequent star formation will alter the size of the merger remnant. One way of identifying recently formed ellipticals at high redshift might be by looking for signs of recent star formation. If there is sufficient gas involved in the major merger, simulations show that a starburst will be ignited (e.g. Barnes & Hernquist 1992) whose signature may be measurable.

Our results presented here support a picture in which ellipticals form in mergers. Future observations of high redshift ellipticals will allow one to make more accurate comparisons to the model we introduced here and will allow us to estimate the role of dissipational processes during major mergers of galaxies.

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